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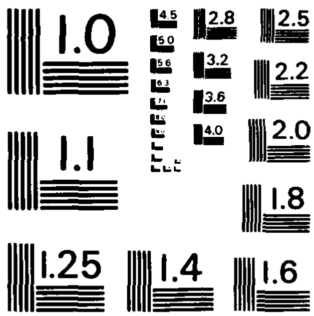

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The large amplitude waves observed in ship wakes and the large radar returns, including sharp angular dependencies, suggest that first order Bragg scattering theory is inadequate to describe the experimental data.

This report considers a simple theory which concludes that there can be look angles such that second order scattering can be larger than first order. These conclusions are very tentative because of the lack of knowledge of the basic wave fields.

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Multiple Scattering Effects in Radar Observations of Wakes

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August 1984

JSR-84-203B

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MULTIPLE SCATTERING EFFECTS IN RADAR OBSERVATIONS OF WAKES

I. Introduction

The large amplitude waves observed in ship wakes and the large radar returns including sharp angular dependences suggest that first order Bragg scattering theory is inadequate to describe the experiments.

Here we consider a simple theory to qualitatively investigate higher order effects. There are two important limitations.

(a) We restrict our consideration to a simple scalar problem with simple boundary conditions. A full scale theoretical treatment of the true electromagnetic problem can readily be carried out. However, it is much more complicated, probably obscures the central points, and in view of (b) probably unwarranted at this point.

(b) The detailed nature of the scattering wave field is very poorly known. To get some insight we have applied the formula to an

idealized mathematical description of a Kelvin wake and to a model "derived" from the Dabob Bay experiments.

The essential conclusions are that there can be look angles such that second order scattering can be larger than first order and comparable in magnitude with the first order scattering when that is significant.

We emphasize the weakness of the conclusions because of the lack of detailed knowledge of the basic wave fields. Recommendations to obtain the needed information are made.

II. A Simple Theory

We consider the electromagnetic field to be described by a simple scalar field satisfying the wave equation.

$$(\nabla^2 + k^2)\,\phi = 0\ . \qquad (1)$$

An incident field

$$\phi_i = e^{i(\underset{\sim}{k}_h \cdot \underset{\sim}{r} - k_v Z)} \qquad (2)$$

$$(\underset{\sim}{k}_h^2 + k_v{}^2) = k^2$$

is to be scattered by a patch of a wavy surface centered on the plane $Z = 0$, i.e., the surface S is

$$Z = h(x,y) \qquad (3)$$

where h is to be small.

As a simple boundary condition we choose $\phi = 0$ on S .

We decompose the total field ϕ into

$$\phi = \phi_o + \Delta\phi \ . \tag{4}$$

Here ϕ_o is the field which would result if $h = 0$.

i.e. $$\phi_o = e^{i\,\underset{\sim}{k}_h \cdot \underset{\sim}{r}} \{ e^{-i\,k_v Z} - e^{i\,k_v Z} \} \tag{5}$$

Further we introduce a Green's function $G\,(\underset{\sim}{r}', \underset{\sim}{r})$ satisfying

$$\nabla'^2\, G\,(\underset{\sim}{r}', \underset{\sim}{r}) = \delta(\underset{\sim}{r} - \underset{\sim}{r}') \tag{6}$$

and $$G\,(x', y', o; \underset{\sim}{r}\,) = 0 \tag{7}$$

Applying Green's theorem we obtain

$$\Delta\phi\,(\underset{\sim}{r}) = {}_S\!\int \{ \Delta\phi(\underset{\sim}{r}') \frac{\partial}{\partial n'} G(\underset{\sim}{r}',\underset{\sim}{r}) - G(\underset{\sim}{r}',\underset{\sim}{r}) \frac{\partial\Delta\phi}{\partial n'} (r') \, dS' \ . \tag{8}$$

For a perturbation theory we assume $h \sim \varepsilon$ and consider a formal expansion in ε .

Then $$\Delta\phi(\underset{\sim}{r}) = \varepsilon\phi_1(\underset{\sim}{r}) + \varepsilon^2\phi_2(\underset{\sim}{r}) + \ldots \tag{9}$$

Restricting ourselves up to second order terms this can be written

$$\Delta\phi(r) = \int\int dx'dy' \quad \Delta\phi(r') \frac{\partial}{\partial Z'} G(\underset{\sim}{r}', \underset{\sim}{r}) - G(\underset{\sim}{r}', \underset{\sim}{r}) \frac{\partial\Delta\phi}{\partial Z'} \tag{10}$$

We readily construct

$$G(\underset{\sim}{r}', \underset{\sim}{r}) = \frac{-i}{(2\pi)^2} \int \frac{d^2K\, e^{i\,[K_x\,(x-x') + K_y(y-y')}}{2\mu} \{\ \}$$

$$\{\ \} = e^{i\mu(z-z')} + e^{-i\mu(z-z')} - e^{i\mu(z+z')} - e^{-i\mu(z+z')}$$

Then to first order we have

$$\phi_1(\underset{\sim}{r}) = \int\int dx'dy' \ \phi_1(x', y', 0) \frac{\partial}{\partial Z'} \ G(x', y', 0; \underset{\sim}{r}) \tag{11}$$

But $\quad \epsilon\phi_1(x', y', h) + \phi_o(x', y', h) = 0$

$\therefore \quad \phi_1(x', y', 0) = 2ik_v h\, e^{i\underset{\sim}{k}_\perp \cdot \underset{\sim}{r}'}$

and $\quad \frac{\partial}{\partial Z'} G(x', y', o; \underset{\sim}{r})$

$$= \frac{1}{(2\pi)^2} \int\int d^2k\, e^{i\,[k_x(x-x') + k_y(y-y')]} \{e^{i\mu Z} - e^{-i\mu Z}\} \tag{12}$$

Thus

$$\phi_1(\underset{\sim}{r}) = 2ik_v \iint dx'dy' \frac{1}{(2\pi)^2} \int d^2 ke^{i(k_x x + k_y y)} [e^{i\mu Z} - e^{-i\mu Z}]$$

$$x\ h(x', y')\ e^{i[(k_x^i - k_y)\ x' + (k_y^i - k_y)\ y']} \tag{13}$$

Now if we write

$$h(x', y') = \frac{1}{(2\pi)^2} \int d^2q\ \ \hat{h}\ (\underset{\sim}{q}')\ e^{-i\ \underset{\sim}{q}' \cdot \underset{\sim}{r}'} \tag{14}$$

Then

$$\phi_1(\underset{\sim}{r}) = 2ik_v \frac{1}{(2\pi)^2} \iint d^2q'\hat{h}(\underset{\sim}{q}')\ e^{i[(k_\perp - \underset{\sim}{q}) \cdot \underset{\sim}{r}]} \left(e^{i\mu(k_i - \underset{\sim}{q})Z} - e^{-i\mu(k_1 - \underset{\sim}{q})Z}\right) \tag{15}$$

From Equation (8) we then read off that

$$\phi_2(\underset{\sim}{r}) = \iint dx'dy'\ \phi_1(x', y', 0) \frac{\partial^2}{\partial Z'^2} G\ (x', y', 0, \underset{\sim}{r})$$

$$+ \phi_2\ (x', y', 0) \frac{\partial}{\partial Z'} G(x', y', 0; \underset{\sim}{r})$$

$$- h \frac{\partial}{\partial Z'} G(x', y', 0; \underset{\sim}{r}) \frac{\partial}{\partial Z'}\ \ \phi_1\ (x', y', 0)$$

<u>Note</u>: With our boundary condition

$$\frac{\partial^2 G}{\partial Z'^2}(x', y', 0; \underset{\sim}{r}) = 0 \quad .$$

Also $\quad \epsilon\phi_1(x', y', h) + \epsilon^2 \phi_2(x^1, y^1, 0) + \phi_o = 0$

But to order ϵ^2 we have $\left.\frac{\partial^2 \phi_o}{\partial Z'^2}\right|_{Z' = 0} = 0$

$$\therefore \qquad \phi_2(x', y', 0) = -h \frac{\partial}{\partial Z'} \phi_1 (x', y', 0)$$

and so

$$\phi_2 = -2 \iint dx'dy' \; h \frac{\partial}{\partial Z'} \phi_1(x', y', 0) \frac{\partial}{\partial Z'} G(x', y', 0; \underset{\sim}{r}) \quad (16)$$

which yields

$$\phi_2 = \frac{-8ik_v}{(2\pi)^4} \iint d^2q' d^2p \; \hat{h}(\underset{\sim}{q}') \; \hat{h}(\underset{\sim}{k}^P) \; \mu(\underset{\sim}{k}_\perp - \underset{\sim}{q})$$

$$x \; e^{i[\underset{\sim}{k}_\perp - \underset{\sim}{q} - \underset{\sim}{p}] \cdot \underset{\sim}{r}} \left\{ e^{i\mu(k_1 - \underset{\sim}{q} - \underset{\sim}{k})Z} - e^{-i\mu(k_1 - \underset{\sim}{q} - \underset{\sim}{k})Z} \right\}$$

In particular if we ask for the amplitude of the wave in the back scattered direction, we obtain

(a) From equation (15)

$$\Phi_1 \approx \frac{2ik_v}{(2\pi)^2} \hat{h}\,(2\,\underset{\sim}{k}_\perp) \tag{18a}$$

(b) From Equation (17)

$$\Phi_2 \approx \frac{-8ik_v}{(2\pi)^4} \iint d^2q \;\; \hat{h}\,(\underset{\sim}{k}_\perp - \underset{\sim}{q})\; \hat{h}\,(\underset{\sim}{k}_\perp + \underset{\sim}{q}) \sqrt{k^2 - q^2}$$

Thus

$$\frac{\Phi_2}{\Phi_1} \approx \frac{-4}{(2\pi)^2} \frac{\iint d^2q\; \hat{h}\,(\underset{\sim}{k}_\perp - \underset{\sim}{q})\; \hat{h}\,(\underset{\sim}{k}_\perp + \underset{\sim}{q}) \sqrt{k^2 - q^2}}{} \tag{19}$$

III. Application to "Mathematical" Kelvin Wakes

Let us now apply these results to the Kelvin wake as computed by simple stationary phase methods. There are many things wrong with this simplest picture of the wake, but we believe that it gives a good enough picture of the wave heights for an analysis of the importance of multiple scattering.

The stationary phase picture asserts that at a point (x,y) in the wake, making an angle θ with respect to the wake axis, the dominant wave vectors in the surface height, h, are

$$k_x = -\frac{g}{2U^2\theta} = -\frac{g}{2U^2}\frac{x}{y}$$

$$k_y = \frac{g}{4U2\theta^2} = \frac{g}{4U^2}\frac{x^2}{y^2}$$

where U is the ship velocity which is in the x direction. This means that the ocean wave height function is

$$h(x,y) = A(x,y) \cos \Phi (x,y)$$

$$\Phi(x,y) = k_x(x,y)\, x + k_y\, (x,y) \cdot y\ .$$

where $A(x,y)$ is a slowly varying function, poorly calculable from stationary phase arguments, and Φ is rapidly varying and, of course, determined by the stationary phase arguments. There are actually two stationary phase solutions for $\vec{k}$: the one given, corresponding to the diverging wave train, and another one corresponding to the transverse wave train. The two trains are displayed in Figure 1. The short wavelengths of direct interest in radar backscatter are to be found in the diverging wave system, so we will not concern ourselves here with the transverse waves. We will later resort to a combination of theoretical argument and direct observation to determine reasonable values for A in various parts of the wake.

To model a SAR observation of the ocean surface, we assume that the radar processing in effect forms a beam which illuminates a patch on the surface of linear dimension b centered on the point (x_o,y_o). The radar return is therefore computed from the formula of the previous section by extending the spatial integrals only over the window $x_o - \frac{b}{2} < x < x_o + \frac{b}{2}$, $y_o \frac{b}{2} < y < y_o + \frac{b}{2}$. The scattered intensity will, of course, depend on the patch size, b.

The scattering formula are expressed in terms of the Fourier transform, $\tilde{h}(\vec{q})$, of the ocean surface. By the preceding remark, we want to compute the transform of the wave height <u>times</u> the radar

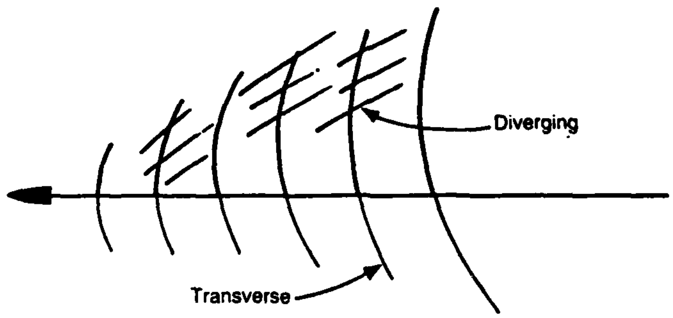

Figure 1. Kelvin Waves

window function. The result for a patch centered on a point at wake angle θ is

$$\hat{h}(\vec{q}) = A(\theta) \int_{-b/2}^{b/2} d\varepsilon d\eta \cos\left(-\left(\frac{g}{2U^2\theta} - q_x\right)\varepsilon + \left(\frac{g}{4U^2\theta^2} - q_y\right)\eta\right)$$

In writing this expression we have simplified the variation of (k_x, k_y) across the radar patch. The omitted effects would contribute terms quadratic in ε and η to the phase of the cosine. We have verified that for parameter values appropriate to the SEASAT or Dabob Bay problems, this approximation is reasonable. The result is

$$h(\vec{q},\theta) = A(\theta)b^2 \text{ sinc } [(q_x + \frac{g}{2U^2\theta}) \frac{b}{2}] \text{ sinc } [(q_y - \frac{g}{4U^2\theta^2}) \frac{b}{2}$$

For our purposes, it suffices to know that $h(\vec{q},\theta)$ has a maximum amplitude of $b^2A(\theta)$ and that it is peaked at the appropriate stationary phase wave number with a width in wave number space of $2\pi/b$.

We are now able to compute the radar backscatter amplitude in first and second Born approximation. According to the previous section,

$$\Phi_1 = C\, \hat{h}\, (2\vec{k}_h, \theta)$$

$$\Phi_2 = -iC \int \frac{d^2q}{(2\pi)^2} 4 \sqrt{k^2 - q^2} \quad \hat{h} (\vec{k}_h + \vec{q}, \theta) \hat{h} (\vec{k}_h - \vec{q}, \theta)$$

where k is the magnitude of the radar wave vector, $\vec{k}_h$ is the horizontal projection of that wave vector and C is a common factor of dimension $1/L^2$ which we would need to know in order to get the absolute scattered intensity.

Since $\hat{h}$ is a sharply peeked function of its argument, $\Phi_{1,2}$ will be large only for a narrowly-defined band of θ. If we define

$$\vec{k}_{KELVIN}(\theta) = \left(- \frac{g}{2U^2 \theta} , \frac{g}{4U^2 \theta^2} \right)$$

then the condition for first and second order scattering to be large is

$$\text{first order:} \quad 2\vec{k}_h = \vec{k}_{KELVIN}(\theta)$$

$$\text{second order:} \quad \vec{k}_h = \vec{k}_{KELVIN}(\theta)$$

The angular width of the first-order Born pattern is determined by the width in momentum space of $\hat{h}$ and the rate of variation with θ of k_{KELVIN}. A bit of algebra shows that

$$\frac{\delta\theta}{\theta} \simeq \frac{2\pi}{b \cdot k_{KELVIN}} .$$

If $b \sim 6$ m and $\lambda_{KELVIN} \sim .3$ m (typical values for SEASAT), this gives $\delta\theta/\theta \sim 1/20$. This is very narrow indeed, but not out of line with observations.

Let us finally consider the relative sizes of first and second order scattered amplitudes. Due account being taken of the peek amplitude of $\hat{h}$ and its momentum space width, we find that the maximum backscatter amplitudes in first and second Born approximations are

$$\Phi_1^{MAX} = C \cdot b^2 A(\theta_1)$$

$$\Phi_2^{MAX} = \left(2kA(\theta_2)\right) \cdot C \cdot b^2 A(\theta_2)$$

θ_1 and θ_2 are the (different!) wake angles at which the two types of scattering reach their maximum, k is the radar wave vector and b is the radar patch size. The integral over $\vec{q}$ in the expression for Φ_2 is, because of the narrowness in wave vector space of the function $\hat{h}$ concentrated at $\hat{q} = 0$, leading to a considerable simplification in the formulas.

We expect that $A(\theta)$ is a reasonably slowly varying function of θ, except in the near neighborhood of $\theta = 0$. Therefore, to compare first and second order scattering we will assume that $A(\theta_1) \sim A(\theta_2)$, obtaining

$$\frac{\Phi_2}{\Phi_1} = 4kA = 8\pi A/\lambda_{radar}$$

From slender ship theory we extract the result that the amplitudes of the diverging and transverse wave trains are related by

$$A_{diverging} \sim \theta^{3/2} A_{transverse}$$

for θ *not too small*. One readily finds transverse wave amplitudes of .5 m a kilometer behind a large ship. This would correspond to a diverging wave amplitude of 1.5 cm at $\theta = 6^o$. We will, therefore, take 1 cm as a representative value for $A(\theta)$. This is confirmed by the in situ wave height measurements of the Dabob Bay experiment. For a radar wavelength of 23.5 cm (appropriate to all the measurements under discussion) we therefore have $\Phi_2/\Phi_1, \sim 1$.

Our conclusion is that surface ship Kelvin wakes are strong enough that multiple scattering from the wake itself cannot be neglected.

At a minimum, this means that multiple returns, due to various orders of scattering ought to be seen. This might be the explanation of the multiple V structures seen in some SEASAT pictures.

IV. Dabob Bay

In the Dabob Bay experiment, the radar return from a wake was measured and the actual wave height was measured in a one-dimensional transverse cut across the wake. The maximum radar return came from points at wake angle $\theta \sim 3.6^0$. The direct measurement of the wave height in this region indicates that there is little energy at wave numbers appropriate to first order scattering and a substantial peak at wave numbers appropriate to second order scattering. This peak does not occur at the wave number predicted by simple Kelvin theory. This is a hydrodynamic puzzle about which we can say nothing. The question of interest to us is whether, given the measured surface height, it is reasonable that second order scattering should overwhelm first order scattering.

The r.m.s. displacement recorded at the interesting wake angle appears to be about 1 cm, and corresponds to surface wavelengths of order 40 cm. As was noted in the previous section, the quantity 2kA, which determines the relative amplitude of second and first Born scattering for equal rms surface displacement, is of order 1 for $A \sim 1$ cm and $\lambda_{radar} = 24$ cm. An examination of the power spectral density of the surface slope shows that the p.s.d. is down by a factor of 10^{-2} from the peak value at the wave number appropriate to first

order Born scattering. Consequently, the intensity of second order Born scattering should be about 10^2 times that of first order Born scattering.

So, if we modify our scattering theory to include higher order effects, there is no inconsistency between the location of the intense radar returns within the wake and the directly observed wake structure. Obviously, one should combine the <u>observed</u> wake structure with a radar scattering model to obtain a predicted radar wake structure and attempt a detailed comparison with the observed radar wake images. An important missing element is a two-dimensional map of the wake structure since that is what really enters the radar cross-section. We have used a one-dimensional wake crossing measurement for rough comparison purposes, but must be aware that surprises may occur when we confront the two-dimensional data derived from photographic images of the wake.

V. Conclusions

These are based on a simplified scattering model and some questionable assumptions as to the nature of the scattering field. The scattering model can be readily improved. Thus with an increase in the complexity of the formula intrinsically electromagnetic effects (such as polarization, Fresnel diffractions, and dielectric properties can be included. This hardly seems warranted till more is known about the hydrodynamic structure of the wake.

Two hydrodynamic descriptions have been used.

(a) The idealized mathematical Kelvin wake.

(b) Some estimates have been made using the Dabob Bay data.

Our conclusion is that first order Bragg theory is not generally adequate. At some viewing angles there will be strong first order Bragg scattering with a sharp angular dependence. At other angles first order Bragg scattering will be small. However, there can be second order Bragg scattering of an intensity comparable to that where first order is large. The angular width of the second order observations should be greater than that of first order, but not necessarily dramatically so.

The main limitations on our present work is that only special directions of look are adequately described. Dabob Bay experiments are closest to what are considered.

To compute what should be observed at other aspect angles empirical two dimensional wave height spectra are needed. Given these the conclusions drawn about angular sharpness might be modified. These also might help us to understand the experiment observations at different aspect angles.

Some of the needed information could perhaps be obtained by reworking the Dabob Bay data. Also some of this might be obtained from the NOSC data.

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